SIZE AND SHAPE EFFECTS ON TWO-PHASE FLOW INSTABILITIES IN MICROCHANNELS

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ABSTRACT

An integrated microchannel heat sink consisting of shallow, trapezoidal microchannels has been fabricated using standard micromachining techniques to highlight the effects of the micrometer sized channel shape on the evolving flow patterns and, consequently, on the thermal response of the system. An integrated heater provides the local heat source, while an array of temperature microsensors is used for temperature distribution measurements. DI water, serving as the working fluid, is pressurized through the microchannels for forced heat convection. Temperature plateaus are observed in the boiling curves, corresponding to the latent heat of phase change of the working fluid from liquid to vapor phase. The evolving two-phase flow patterns have been recorded and analyzed using high-speed camera. Bubble formation, growth and detachment at specific nucleation sites have been observed. Annular flow mode has been found to be unstable in trapezoidal channels. Instead, a highly unsteady transition region from upstream vapor phase to downstream liquid phase flow is developed, and the average location of this region depends on the input power.

INTRODUCTION

Two-phase convective flow has numerous promising applications such as cooling of electronic components [1]. The principal advantage of two-phase flow lies in the utilization of latent heat absorbed by the working fluid due to phase change from liquid to vapor without any temperature increase. Furthermore, for unsteady thermal performance, the response time of either heating-up or cooling-down process under forced convection is significantly shorter than under free convection heat transfer [2].

Convective heat transfer in macrosystems has been studied extensively. However, research on the effects of the channel size and shape on two-phase flow patterns in microchannels is very limited, especially in systems with a length scale on the order of 10μm or less. While gravity and pressure gradient are the dominant forces in macrosystems, surface tension is negligible. In microsystems, on the other hand, gravity is negligible but surface tension becomes a dominant force. Consequently, two-phase flow is an ideal example to illustrate the physics of scaling problem in microsystems.

Indeed, the thermal performance of a microsystem depends on the evolving flow pattern [3]. Peng and Wang [4] experimentally investigated the phase change in microchannels and found that the boiling regime was fully developed nucleate boiling and bubbles did not grow in microchannel boiling. Browers and Mudawar [5] reported vapor bubbles activity in microchannels that resulted in enhanced heat transfer rate and increased pressure drop. They also observed a plateau in the boiling curve. In contrast, Jiang et al. [6] observed no plateau in the boiling curve of triangular microchannels. Peles et al. [7,8] conducted experiment and analysis of forced convection boiling in a microchannel, in which single bubbles as well as vapor-liquid interface within the channels were observed. Zhang et al. [9] showed that the dimensions of a rectangular microchannel were critical for the flow pattern and the thermal response. In this work, trapezoidal-shaped microchannels are designed and fabricated to perform as a micro heat sink in order to demonstrate the shape effect.

DEVICE DESIGN AND FABRICATION

Standard micromachining techniques were utilized in the fabrication of the integrated microsystem [4]. The micro heat sink, fabricated on a p-type silicon wafer, consists of 10 microchannels (Figure 1) integrated with a local heater and a temperature microsensor array (Figure 2). A glass wafer, with inlet/outlet holes, was anodically bonded to the silicon substrate to cap the grooves. The resulting micro-channels with a transparent cover allow video recording of the evolving flow patterns during operation. The integrated heater at one edge of the device functions as the heat source. A 10x10 array of temperature microsensors was fabricated for detailed temperature distribution measurements. The heater and temperature sensors were formed using a selectively doped 0.4μm-thick polysilicon film.

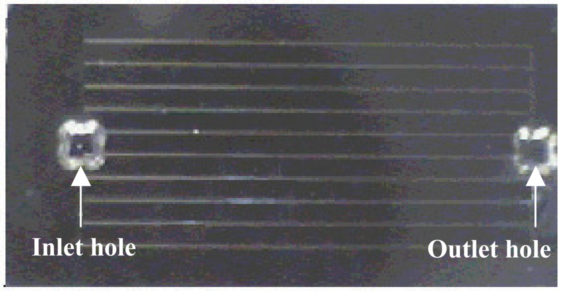

Fig 1: A picture of the device front-side showing the microchannels with the common inlet/outlet holes.

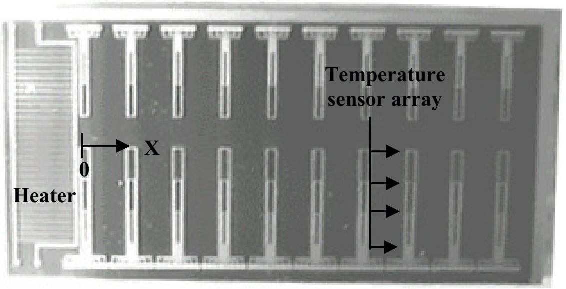

Fig 2: A picture of the device back-side showing the temperature sensors, heater and metal lines.

The overall area of a die is 10x20mm^2. The microchannels are 18mm in length, formed by Si etch in TMAH. An SEM picture of the trapezoidal cross-section is shown in Figure 3, where the depth is 14µm and the average width is 120µm. Each die was packaged and wire bonded to facilitate connections to the external fluid handling system as well as the electronic equipment for I/O signals.

EXPERIMENTAL SET-UP

DI Water contained in a pressurized tank was forced through the microchannels by an adjustable high-pressure gas source. The fluid exiting the micro heat sink was cooled and condensed by passing it through cold water. The condensed water was then collected in a graduated cylinder to measure the volume flow rate.

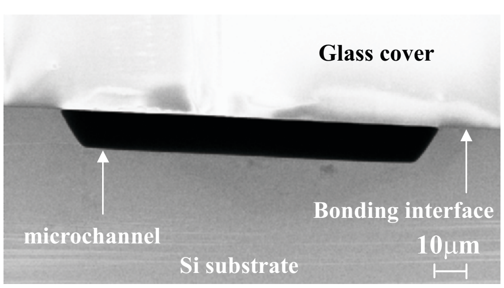

Fig. 3: A SEM cross-sectional picture showing the trapezoidal shape of a microchannel 14µm in depth.

The input power was controlled by adjusting the voltage applied to the heater. The temperature sensors output signals were recoded using a computerized data acquisition system. The flow patterns were simultaneously recorded using a high-speed camera mounted on a microscope.

RESULTS AND DISCUSSION

Temperature distribution measurements along the device centerline are summarized in Figure 4 for various input power levels and a constant water flow rate of 0.0315mL/min. The temperature of the microdevice increases with input power. When the input power is low, the temperature distribution is almost uniform. As the input power is increased, the temperature gradient along the device also increases.

The boiling curves, shown in Figure 5, exhibit the plateau associated with latent heat of phase change from liquid to vapor where $\partial T/\partial q \cong 0$. The local temperature initially increases linearly with the input power, up to a level about 1.85W. Further power increase leads to a phase change of the water from liquid to vapor, as the void fraction increases with input power. The onset of critical heat flux (CHF) condition develops at a power level higher than 2.05W. Then, the temperature everywhere increases sharply, as the entire flow is in single vapor phase. In previous studies [4,10], however, no plateau was observed in the boiling curves of heat sinks with either triangular- or diamond-shaped microchannels. In the triangular cross-section microchannels, a stable vapor core was established at a relatively low input power, suppressing the development of bubbly flow. Consequently, the temperature increased smoothly, though with decreasing slope, with no classical boiling plateau. This was attributed to the geometry effect on the flow pattern, which developed during forced convection boiling in these microchannels.

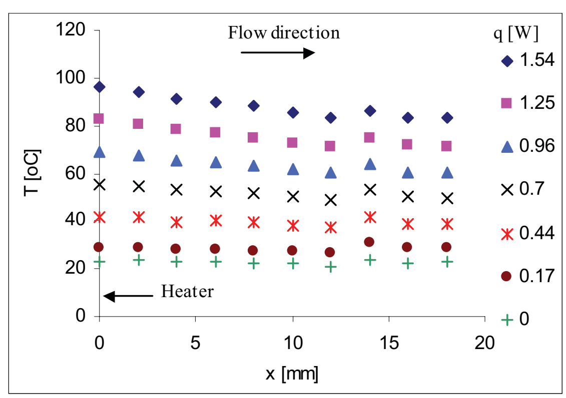

Fig 4.: Temperature distributions along the device centerline, T(x), as a function of the input power q.

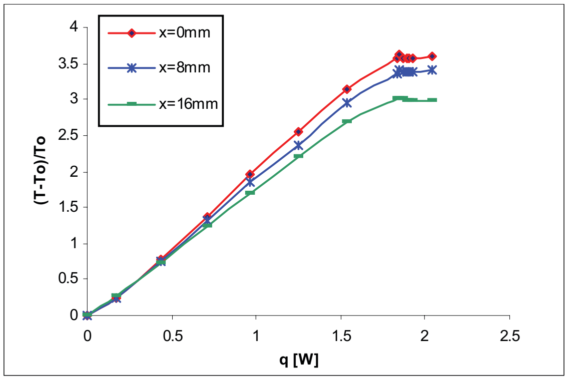

Fig. 5: Boiling curves of the device temperature as a function of the input power under forced convection.

Flow visualizations using high-speed camera reveal a sequence of flow patterns that cannot be observed otherwise. Bubble formation, growth and detachment (Fig.6) are rather unique when operating temperature is lower than the water saturation temperature. The nucleation sites are always at defects, such as pinholes formed during etching, along the channels. In classical bubble dynamics, the bubble explodes when the pressure difference overcomes the surface tension. However, due to geometric constraint in a microscale, the bubble occupies the entire channel. Resting against the solid walls, it becomes stable. A very long tail connects the bubble to its nucleation site (Fig.6a). Only when the surface tension along the tail overcomes the internal pressure, and both interfaces merge, does the bubble depart. The bubble then loses its distinct boundary (Fig.6b), but it does not re-condense since it re-forms upon impingement on the channel exit. Since the bubble does not re-condense to liquid phase even after exiting the microdevice, it is expected that the bubble come from dissolved gas in the DI water.

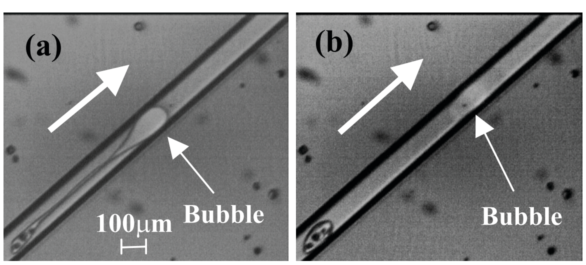

Fig. 6: High-speed camera pictures of: (a) bubble growth, and (b) departure from a nucleation site.

An annular flow field could develop in the microchannel as demonstrated in Figure 7. However, this flow mode is highly unstable and, within 0.3sec of its formation, Figure 7a, the two liquid films from both sides of the vapor core are attracted to each other due to surface tension. When the two liquid films merge, Figure 7b, the vapor core snaps immediately and the annular flow mode disappears. This is exactly opposite to the triangular microchannels, where the annular flow was the most stable mode [4].

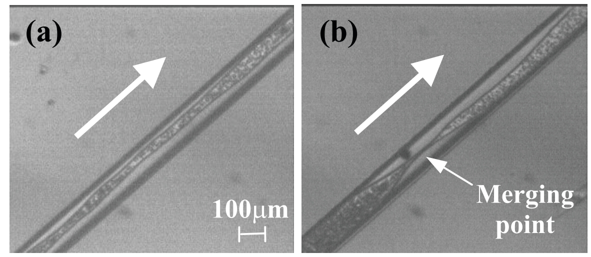

Fig. 7: High-speed camera pictures of (a) formation, and (b) collapse of an annular flow mode.

The most prevalent flow pattern observed is a transition region separating an upstream vapor zone from a downstream liquid zone. The transition region seemed to oscillate randomly along the microchannel with no clear structure. However, under a high-speed camera, a fascinating orderly pattern is observed as detailed in Figure 8. Upstream of the transition region, Figure 8a, the flow is in single vapor phase, since the heater is located at the channel inlet. At the upstream tail of the transition region, Figure 8b, liquid droplets start to condense on the colder channel ceiling. The liquid droplets increase in number and size, Figure 8c, until two condensed liquid films are formed on both sidewalls, Figure 8d. Thus, an annular flow pattern is developed as shown in Figure 8e. Since the channel height is very small, about 14μm, the liquid films grow in the spanwise direction, Figure 8f. When this occurs, a vapor region with liquid droplets at the downstream end of the transition region is severed from the upstream vapor flow, Figure 8g. Finally, after the two liquid films merge together, the upstream vapor region is completely snapped from the main supply, Figure 8h. Immediately the liquid interface moves downstream, and the cycle repeats itself resulting in an intermittent flow downstream of the transition region. The transition region oscillates significantly along the microchannel with rather large amplitude, and its average location depends on the input power. At a power level corresponding to the start of the boiling plateau, the transition region appears from near the channel inlet. As the input power increases, the transition region moves downstream, and appears around the channel outlet when the input power reaches the CHF level.

These two-phase flow instabilities in micro-channels are attributed to size and shape effects, since in channels with triangular cross section, annular flow with a stable vapor core was the dominant flow mode.

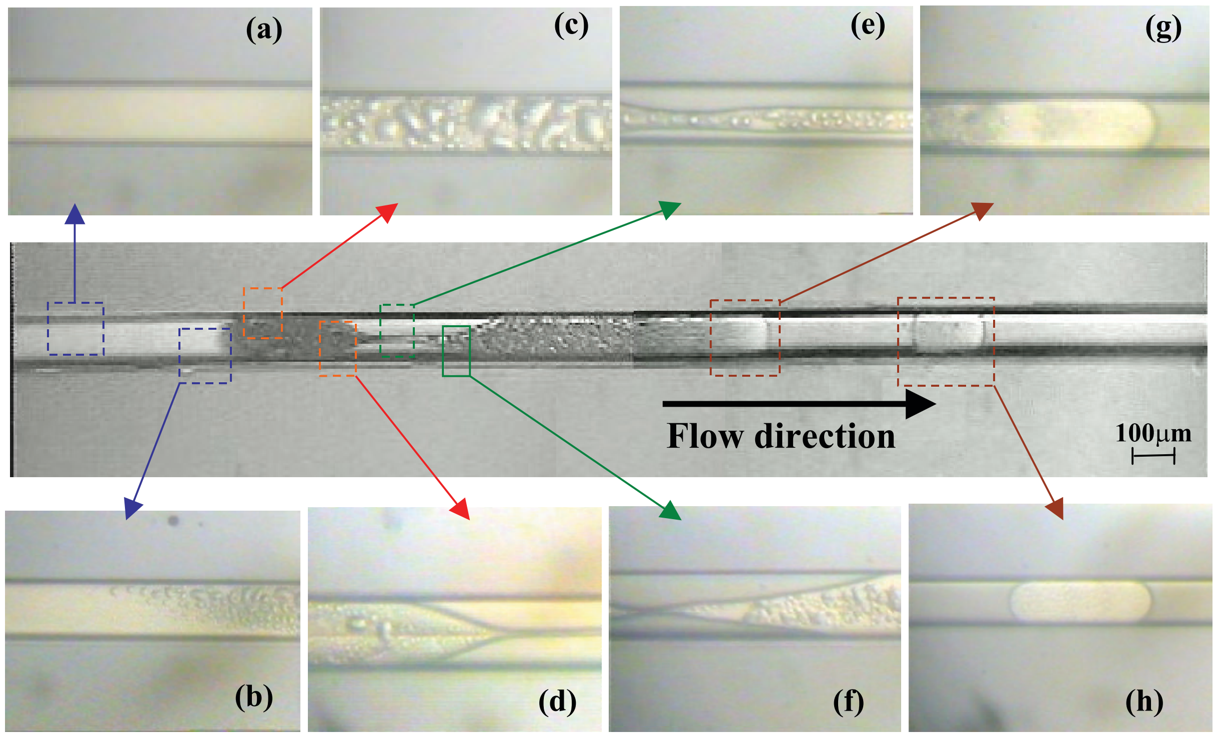

Fig. 8: A sequence of pictures, a-b-c-d-e-f-g-h, detailing the transition region from the upstream vapor (a) to the downstream liquid zone (h) in two-phase convective boiling flow. Flow direction is from left to right.

CONCLUSIONS

A microchannel heat sink integrated with a local heater and array of temperature microsensors has been fabricated and characterized. Two-phase flow patterns, developed during convective boiling in microchannels, demonstrates both size and shape effects. On a microscale, surface tension becomes a dominant force while gravity is negligible. Bubble formation, growth and departure can still be observed. However, the bubble departs when the surface tension exceeds the internal pressure at the bubble tail. An unstable annular flow pattern is observed, but it is highly unstable due to the trapezoidal shape of the channel. Consequently, a transition region between the upstream vapor and the downstream intermittent flow is developed. The transition region oscillates violently along the channel, and its average location moves downstream with increasing input power. Thus, the increased power is converted into latent heat of the working fluid. As a result, the associated plateau is observed in the boiling curves.

ACKNOWLEDGMENTS

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